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PSYCHOPHYSIOLOGICAL EFFECTS OF EXTREMELY LOW FREQUENCY ELECTROMAGNETIC FIELDS: A REVIEW

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Summary.—Extremely low frequency (ELF) electromagnetic field-waves, defined in this paper as occupying the frequency band of .01 to 100 Hz, are associated with geomagnetic disturbances, weather perturbations, electrical appliance discharges, and possibly seismic movements. ELF electromagnetic phenomena have been recorded as sinusoidal-like wave forms or as ELF pulses of short duration from higher frequency (10 to 100 kHz) waves. Although natural ELF electrical component intensities range from less than 1 mV/m to slightly more than 1 V/m with magnetic components less than a μ gauss and calculated power densities of 10^{-8} watts/m^2, these waves can propagate long distances without appreciable attenuation and penetrate housing structures. Theoretically, it has been calculated that energy available from ELF phenomena can contribute to neuroenergetic functioning and protein-lipid activity. Correlational and experimental data indicate that ELF fields can influence reaction time, timing behavior, ambulatory behavior, oxygen uptake, endocrine changes, cardiovascular functions, and precipitation-clotting times of colloids. Possible mechanisms of ELF-organismic interactions are discussed.

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Electromagnetic field-waves in frequency bands of electrical processes in living organisms have been measured in our environment. These extremely low frequency (ELF) fields have the capacity to penetrate buildings and living tissue and hence are potential biological stimuli. In 1954 Sundermann reviewed the area and concluded that there were insufficient data to support the role of ELF electromagnetic phenomena as important meteorogenic stimuli. However, with the greater interest in environmental and space research and increasing reports on significant effects from these fields, another review is required.

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Physical Characteristics

Electromagnetic fields, waves and impulses which occupy the frequency band between 3 Hz and 3 kHz have been termed ELF or extremely low frequency (Campbell, 1967). Very low frequency or VLF (3 kHz to 30 kHz) and ultra low frequency or ULF ($<$ 3 Hz) phenomena occupy adjacent wavebands. In this review article, however, time-varying magnetic, electric, and electromagnetic phenomena ranging from .01 Hz to 100 Hz will be designated as ELF, since this range overlaps with major time-varying electromagnetic-biochemical processes in living organisms.

ELF fields may occur in nature as a pure wave or may be presented as ELF pulses from VLF carrier waves. In the latter case, VLF waves, e.g., 10 kHz, are received as short pulses lasting 10^{-1} to 10^{-4} sec., the number of pulses per second (pulse frequency) being in the ELF range (Al'pert & Fligel, 1970; Ranscht-Froemsdorff, 1968; Large & Wait, 1968). The sources of ELF and VLF fields are primarily ionospheric above 4 Hz to 7 Hz and magnetospheric below these values (Campbell, 1967). ELF phenomena associated with local weather conditions seem to span the entire ELF spectra. Artificial sources of ELF also contribute to the EM noise.

Ionospheric origins seem to come mostly from lightning discharges called atmospherics or 'sferics'. Chapman and Mathews (1953) have demonstrated that the amplitude spectra of atmospherics show maxima at 30 Hz to 100 Hz and 10 kHz, with a minimum between 2 kHz to 3 kHz. At 5 Hz, the magnetic component is about 10^{-8} gauss while the electrical component would be about 2 mV/m. By 400 Hz, these perturbations have fallen to less than 10^{-11} gauss and 2 μV/m, respectively (Willis, 1948). At the lower end of the ELF band, where the wavelength begins to approximate the circumference of the earth (40,000 km), a unique resonance system is produced (Schumann, 1957). Power spectra of Schumann resonances show maxima at 7.8, 14.1, 20.3, 26.4, and 32.5 Hz, with electric field strengths up to 1 mV/m. Power level decreases as the frequency increases (Toomey & Polk, 1970), while the propagation parameters depend on the boundary characteristics of the ionosphere (Galejs, 1970). The principal amount of ELF energy remains within the spherical shell between the earth and ionosphere. Consequently, ELF waves in this mode can travel around the earth without appreciable attenuation. A typical attenuation rate is .8 db/Mm (Taylor & Sao, 1970). This means that a 1 mV/m wave at the source will decrease to about .9 mV/m after traversing a million meters within the spherical wave guide. The frequency of resonance depends on the distance between the source and receiver (Large & Wait, 1968). ELF emissions are at times observed near 4 Hz to 9 Hz. They are so termed because of the difference between these frequencies and the fundamental Schumann frequencies at 8 Hz to 14 Hz (Saito, 1969).

These resonances as well as VLF waves originate primarily from thunder-

storm activities (Galejs, 1964) in the active areas of equatorial Africa, south-east Asia, and in a belt running from southern North America to central South America (Sparrow & Ney, 1971). Increases of 25-Hz to 100-Hz waves, with 10-kHz to 25-kHz components have been correlated with peak thunderstorm activity in the Amazon Valley and Central Africa (Holzer & Deal, 1956). The major sources for at least some areas can apparently shift, depending upon season.

The intensity and number of ELF waves and pulses show diurnal and seasonal variation. Both 9-Hz fields in Germany (Konig, 1962) and 50-Hz to 300-Hz fields in North America (Holzer & Deal, 1956), displayed amplitude peaks between 14:00 to 16:00 hr. local time and amplitude minima between 00:00 and 08:00 hr. This variation was most pronounced during the summer months, during which time the peak magnitude was 3 to 10 times that of the intensity of the minima. Tromp (1970) has reported pulses of 3-kHz to 50-kHz waves of .01 to .2 V/m exhibit a maximum between 23:00 and 07:00 hr. with a minimum between 10:00 and 16:00 hr. during January through March. A second maximum occurred during May to August at 14:00 to 16:00 hr. with a minimum at 08:00. Tromp indicated that the number of impulses rapidly increased in May and June, with a maximum in August.

Reception frequency also seems to follow a day-night change. Surprisingly, Konig (1962), who summarized the work of several experimenters, found that fields below about 130 Hz were received more in the day while higher frequencies dominated at night. Attenuation for 50-Hz to 300-Hz waves is about 2.3 db/Mm in the day and 1.6 db/Mm at night (Hughes & Theisen, 1970), a value which depends strongly upon the local magnetic field dip angle. At night (Hughes, 1967), W-E propagation shows less attenuation than E-W propagation (Taylor & Sao, 1970).

ELF phenomena associated with geomagnetic disturbances are often sinusoidal wave forms which occupy the frequency range from 3.5 Hz to 0.15 Hz (Campbell, 1967) and are often called pearls, hydromagnetic (hm) emissions, or pc 1 (continuous pulsations). On the average, these events last about 35 min. with amplitudes quite small, rarely exceeding a gamma (10^{-5} gauss). Waves in the outer magnetosphere often show higher intensities (3 to 8 gamma). Diurnal variations are apparent, but no seasonal periodicities have been noticed. It has been suggested that geomagnetic micropulsations originate from hydromagnetic waves in the magnetosphere which propagate down the earth's flux lines to the surface (Jacobs, 1970; Patel & Cahill, 1964). Hz waves apparently originate from solar plasma-induced disturbances in the outer magnetosphere and are affected by varying refractive indices of the ionosphere and magnetosphere following local changes in current-carrying regions (Abbas & Poverlein, 1968). A recent review on geomagnetic pulsations has been prepared by Saito (1969), and McPherron, Russel, and Coleman (1972).

Several authors have shown a correlation between weather conditions and

ELF electromagnetic waves and pulses. Konig (1962) noticed that, unlike the 9-Hz waves (Type I) associated with strong lightning, 2-Hz to 6-Hz waves (Type II) were top-waved and were connected with rain and heavy, deep lying clouds. These frequencies did not show diurnal variation and were observed sometimes for hours with pulse intensities up to 0.1 V/m. Frequencies of 0.5 Hz to 2 Hz (Type III) were recorded with sinusoidal wave patterns, but their origin was unclear. Local lightning strokes were also recorded as impulses with about a half-second duration from trough to trough. During sunrise a unique 9-Hz wave which was later dominated by a 3-Hz to 4-Hz band occurred. Reiter (1964) has published considerable data implicating the association between unstable air masses and pulses in the 4-kHz to 12-kHz and 10-kHz to 50-kHz spectra. In Europe polar air masses were correlated with decreased numbers of atmospherics (pulses) in the summer and early autumn but increased pulses during winter and spring. On the other hand, maritime and tropical air masses decreased these pulse counts in winter and autumn and increased them in summer. During stable weather conditions, ELF pulse frequencies of 1 Hz to 3 Hz superimposed upon a 10-kHz carrier wave have been demonstrated. Local unstable weather conditions, such as the close passage of a cold or warm front, result in marked increases in the incidence of 30-Hz to 100-Hz pulse frequencies superimposed upon a 10-kHz to 100-kHz carrier (Lotmar, Ranscht-Froemsdorff, & Weise, 1969). The latter fields varied from .01 to .1 V/m, and were propagated with retention of appreciable strength from 10 km to 100 km from the frontal or low pressure turbulence system. Ormenyi (1972) reported that the lower end of the ELF band (3 Hz) may show greater weather specificity, at least in Hungary. He found an increase in this band's power spectrum during cold front passages and labilization processes but a decrease during warm front passages, upgliding processes and influxes of subtropical air masses in the higher levels of the atmosphere. Wave patterns near the source area favor impulse cascades and statistical fluctuations in contrast to a nearly constant frequency series for very distant sources, in which case the lower ELF resonances are more pronounced. In some areas the pulse frequency might vary from 100 Hz down to .01 Hz. Local factors can also influence the incident frequency and intensity of ELF fields. These include local water level, mineral content, topography and altitude. For example, Ranscht-Froemsdorff (1969) has reported gains as high as 60 db (e.g., from 1 mV/m to 1 V/m) between water-poor valleys and higher plains with underground water sources. Changes of this magnitude have even been recorded between two points 100 m apart, a marked local variation.

Few geophysical events seem to be consistently and significantly correlated with ELF electromagnetic fields measured at various stations. In 1953 Aarons and Henissart reported no significant correlations between ionospheric storminess, solar flares or geomagnetic perturbations and ELF waves on the earth's sur-

face. These authors mentioned a 1-Hz to 20-Hz wave phenomenon which closely followed diurnal geomagnetic activity and a significant correlation (.57) between 20-MHz solar radio noise and ELF waves 29 days later. Ormenyi (1972) noted that in 1969 increased 3-Hz sferic levels were correlated with solar flares while decreased 3-Hz levels seemed to follow geomagnetic storms followed by particle invasion. The implications of these observations are still unclear. However, solar involvement in geo-ELF processes was hypothesized as early as 1948 by Menzel and Salisbury.

Two other possible sources of ELF fields have been suggested. Ranscht-Froemsdorff (1969) noted that defective electrical fixtures, such as a fluorescent lamp, can produce ELF pulses up to 1 V/m. These disturbances along with normal household electrical variations may summate with ambient natural ELF which enter the house via telephone and power lines. During earthquakes, seismoelectric effects in areas of high quartz concentration could result in ELF wave generation, with frequencies ranging from 10 Hz to well below 1 Hz and a spectral maximum near 1.5 Hz (Finkelstein & Powell, 1970). The seismic wave would provide an effective 1-km^3 antenna carrying a current of 1 A to 10 A at the spectral maximum. Any electromagnetic radiation from 1.5-Hz waves would, according to calculation, be of low power ($<<$ 1 W), although higher frequency transients could be more intense. With seismic stress changes of 10 to 100 bars, potential differences of 10^6 V/m could occur locally and produce bright luminosities or fluorescence in light fixtures.

ELF as Biological Stimuli

ELF electromagnetic fields may be important biological stimuli because of their penetrability and long range of propagation. In addition, their frequency and intensities are within the magnitude and range of living organisms. Compared to other meteorogenic stimuli, ELF-waves and charged ions have the greater capacity to penetrate the microclimate of the average house. Faraday cages, which can significantly shield out radio frequencies, have minimal effect on the ELF band. The transparency of brick-houses to 10-kHz ELF pulse carriers is about 95% of 100 mV/m while a large Faraday cage of 1-mm iron wire with 30-mm mesh-width is about 65%. An atomic bunker, on the other hand, constructed of 60-cm of concrete shows a transparency of less than 1% at these frequencies (Ludwig, Mecke, & Seelewind, 1968). Lower frequencies and longer wavelengths would of course have greater penetrability. Such lower frequencies would be characteristic of waves from more distant energy sources, typically from labile weather fronts two or three days away. Consequently the living organism, even in housing, would be exposed to ELF pulses and waves from both distant and proximal sources.

ELF pulse frequencies and waves occur in the wave band of many electrical processes in mammals. Individual neural activity can occur between $\leq$ 100 Hz

and 1000 Hz, while electrical activity in large areas of the brain (the EEG) ranges from about 1 Hz to over 50 Hz. In fact, Konig (1971, 1962) has repeatedly mentioned the striking similarity in wave form and frequency between ambient Type I (10 Hz) ELF waves and the human alpha pattern and Type II (3 Hz to 5 Hz) waves and delta-wave patterns. Changes in EEG frequencies have long been associated with modifications of subjective behaviors, including "consciousness." The possible influence of alpha frequency electromagnetic fields on alpha rhythm-related behavior has been a major impetus for preliminary work in this area (Hamer, 1965; Konig, 1962). Also in the ELF range are the d.c. or slow potentials of the brain which vary from less than .01 Hz to about a 1 Hz and have been implicated as important correlates for learning and storage of information (Rowland, 1968). Even the microvibrations of the musculature of human organisms occur in this waveband, especially between 4 Hz to 12 Hz (Tishchenko, 1963; Rohracher, 1955).

Despite the synchrony of frequencies between ambient electromagnetic phenomena and electrical processes in mammals, there still has been some question as to the amount of energy available from these fields to the organism. Is there enough energy generated by ELF pulses to affect the nervous system? According to Reiter (1964), sferic frequencies are strongest at 10^4-Hz, which means that at an amplitude of 1 V/cm a current density of 10^{-8} to 10^{-9} A/cm^2 would be triggered in the tissue. He concludes that such current densities would be of sufficient magnitude to trigger processes in the receptors, although direct physicochemical changes in deeper tissue would be unlikely. The energy density available from the above field would be only 10^{-10} W/cm^2, although still considerably greater than the 4×10^{-17} W/cm^2 required to trigger an optical sensation in the adapted eye. However, these calculations give no indication of how effective such frequencies would be to such specialized receptors.

Recently, Ludwig (1971, 1968) has calculated that the amount of energy available from an atmospheric impulse with respect to the area of the cell membrane lies in the magnitude region of the energy in a miniature EPSP. Essentially, by using the vector $\bar{S}$ of the VLF wave, we can calculate the available energy "e" from an atmospheric impulse at time t to be: $e = {}^{4}\int_t \mid \bar{S} \mid dt, = A/120\pi \int_t \mid E \mid^2 dt$ (Ws): and $e \cong \frac{1}{2} \cdot (10^7 A/120\pi) E^2 t$, where E is the vector of the electrical field strength. If $A = 3 \times 10^{-8}$ cm^2, $E = 2 \times 10^{-4}$ V/cm, and $t = 10^{-3}$ sec.. the energy "e" is about 1.5×10^{-14} ergs. Eccles (1964) argues that $.5 \times 10^{-14}$ ergs is released during EPSP phenomena. Ludwig (1971) has also suggested, theoretically, that in areas of high neural membrane density, the effect might be potentiated over larger areas.

Reaction Time Experiments in Human and Non-human Primates

Reiter (1964, 1956, 1953) reported significant correlations between increased pulse counts in the 4-kHz to 12-kHz and 10-kHz to 50-kHz ranges and

changes in reaction time (RT), traffic accidents and industrial accidents. He controlled for confounding factors such as fog and rain, but did not specify pulse frequency. Konig (1962) examined Reiter's data taken from human *Ss*' simple reaction time to the onset of a light and found an increase (slower) in RT correlated with an increase in natural Type II signals (3 Hz to 6 Hz) and a decrease in RT correlated with an increase in natural Type I signals (10 Hz). In a laboratory situation, Konig (1962) recorded human *Ss*' reaction time to the onset of a light during 8-hr. periods with stimulus presentations every 20 min. The use of a warning signal or precise instructions to *Ss* was not reported. An electrical field was created by placing either a 3-Hz or 10-Hz potential, with intensities from 2.5 V to 4.5 V across wire mesh separated by a 2.5-m vertical space (1 V/m to 2 V/m). The results were not statistically significant but replicated the correlational studies. Application of the artificial 3-Hz field was associated with a relative increase in reaction time while application of the artificial 10-Hz field was associated with a relative decrease in reaction time. Unpublished data from the first author's laboratory[1] collected on 40 human *Ss* indicates similar increases in RT to the onset of a light during 3-Hz field exposures and decreases during 10-Hz field application. However the relationship between frequency and RT is by no means clear and seems to depend upon the pattern of RT-stimulus presentations and the sequence of field frequencies applied.

With modification of Konig's methodology, Hamer (1968) exposed human *Ss* to 2-Hz to 12-Hz electric fields produced by a 2-V potential across horizontal plates separated by 45-cm (4 V/m). Simple RT to the onset of a tone was recorded in blocks of 11 min. (24 measurements), with a time of 15 $\pm$ 2 sec. between tone presentations and 15 min. between blocks. Although the logic is not clear from that report, different *Ss* were exposed independently to different combinations of frequencies such as 12 Hz and 6 Hz or 6 Hz and 2 Hz. Hamer (1965) reports that the lower of the two frequencies resulted in a relative increased RT. Interesting aspects of Hamer's research, which are discussed by Konig (1971), involve the apparent sensitivity of human *Ss* to even weaker (0.4 V/m) fields and the possibility that at the lower, more natural intensities, less of a field frequency change is required to produce behavioral effects. One final experiment with human *Ss* and simple reaction time to the onset of a light was conducted by Friedman, Becker, and Bachman (1967). According to their reports, application of a 0.2-Hz modulated magnetic field of 11 gauss resulted in significant increases in RT, while 0.1-Hz and static magnetic fields of comparable intensities had little effect. Why such a small change (0.1 Hz) in field frequency would differentially affect RT is not clear. This field was heavily weighted in the magnetic component. In addition such low frequencies may be coupled to the dc fields of the brain which have been more clearly shown to produce changes in human RT and levels of "consciousness."

Non-human primates also seem sensitive to ELF fields. Grissett and de Lorge (1971) measured the effects of a 3 gauss, 7-Hz and 45-Hz field upon RT, reinforcement ratio and efficiency ratio (correct responses/total responses) in monkeys trained on a S^D — S^Δ schedule. The number of *S*s was too small to make any definite statements. However, two of the three monkeys showed decrements of efficiency ratios during the presence of the 7-Hz field. This is most interesting in context of the study of Gavalas, Walter, Hamer, and Ady (1970) who exposed 2 monkeys, rewarded for pressing a panel once every 5 sec., to either 7-Hz or 10-Hz fields produced by applying 2.8 V across two plates separated by 40 cm. The 10-Hz field had little effect on inter-response time (IRTs) while the 7-Hz field produced significantly shorter IRTs. Analysis of EEG records showed consistent relative power peaks at the frequency of the fields predominantly in the hippocampus with both *S*s. Less consistent peaks were found in the other areas measured—the amygdala and centre median. Since the occurrence of theta (4-Hz to 7-Hz) rhythms in the hippocampus are normally associated with attention, additional power to this frequency range could result in shorter RTs and lower efficiency ratios. The changes in IRT are reminiscent of light flicker effects on temporally conditioned reflexes. Flicker frequencies of 10 Hz and half or double this frequency do not interrupt a temporarily conditioned reflex, while flicker frequencies at 7 Hz or 14 Hz to 15 Hz produce a decrease in reflex intervals (Holubar, 1969). The importance of the applied field frequency being within biofrequency range is suggested in a more recent article by de Lorge (1972). He tested the RT and other behaviors of 3 rhesus monkeys exposed to either an ELF 10 gauss magnetic field or in combination with a 4 V/m electric field and observed no significant changes. However both the magnetic and electrical field frequencies were 75 Hz, considerably beyond demonstrated effective frequencies.

Other ELF-related Behaviors in Human Ss

The human *S*s exposed to the 3-Hz field of Konig's 1962 study reported headaches, fatigue and tiredness within a few seconds of field application. Decrement in skin resistance was also noted in 5 of the 10 *S*s exposed to this frequency at 5 V/m. Similar decrements occur during "emotional" behavior but could be artifactually related in this study to the increased sweating of the palms which was also reported. Although Konig mentions that field-related complaints were later confirmed by Weiner, there is only a passing reference to blind procedures. Ludwig and Mecke (1968) reported a pilot study in which arthritic complaints were recorded following ELF-VLF application. When the exposure antenna was disconnected from the generator without *S*'s knowledge on certain trials, the effect on verbal report was the same as the no-field condition. The report of private behaviors experienced in ELF-experimental situations is probably subject to other controlling stimuli. Unpublished experiments by the first author[1] indicate that in terms of *types* of complaints, 20 human *S*s exposed to 3-Hz or 10-Hz ELF fields

inside a Faraday cage situation do not differ significantly from 20 human *Ss* who were inside the Faraday cage with no field applied. Both groups of *Ss* report pains in the neck, ringing in the ears, apprehension, flushes, stiffness, tiredness, and "slight" headaches.

Collectively, both electrical and behavioral (RT) evidence suggests that the ELF fields may be affecting some aspects of timing-behavior in primate *Ss*. Hamer (1969) found that a 12-Hz 4-V/m field shortened human judgment of a 5-sec. interval relative to a 8-Hz field. The role of the hippocampus in temporal disorientation problems, as well as diffuse subjective complaints similar to those reported in field-exposure situations, has often been noted (Orme, 1969; Crosby, Humphreys, & Lauer, 1962). That at least certain ELF phenomena may affect timing processes in human beings has been strongly suggested by Wever (1968, 1967). He found that human *Ss* placed in an underground bunker showed gradual desychronization and lengthening of circadian rhythms (kidney secretion, body temperature), which could be resynchronized when an artificial 10-Hz, 25-mV/cm field was applied. Since 10-Hz fields show a 3- to 10-fold daily change in amplitude, they could in fact act as Zeitgebers for "switch-overs" in the autonomic nervous system (Konig, 1962). Interestingly, coincident with the maximum in 10-Hz field amplitude between 14:00 and 16.00 hr. in Germany is the minimum estimation period for passage of time (Poppel & Giedke, 1970). Although these facts certainly do not prove that ELF electromagentic pulses are of primary importance as time-givers, they strongly suggest at least a partial role. The "Zeitgeber effect" could be related to the theoretical notion that ELF pulses from the earth-ionospheric cavity were especially intense during pre-Cambrian abiogenesis (Graf, *et al.*, 1967a, 1967b).

Activity Changes and Learning in Rodents and Pigeons

Persinger, Persinger, Ossenkopp, and Glavin (1972) reported that in several experiments, rats exposed for 21 to 30 days to a 0.5-Hz (3 to 30 gauss, 10^{-5} V/m) rotating magnetic field (RMF) displayed significant increases in ambulatory behavior *when removed* from the field. Although this effect was replicated with blind procedures, the possible role of apparatus artifacts was not sufficiently controlled. Other *Es* have used designs where the animal was its own control. Ludwig and Mecke (1968) allowed hamsters to habituate in a Faraday cage during a 3-wk. baseline period. When artificial atmospherics were introduced by an antenna, the activity dropped to half that of baseline. Repeated exposure to artificial fields (1 V/m) with carrier frequencies of 10-Hz to 100-kHz and 20-Hz, 10-Hz, or 5-Hz pulses was also associated with decrements in ambulation. Altmann (1969) reported similar decrements in mice activity following 1.75-Hz and 5-Hz field exposure (40 V). The observation that rodents will avoid high intensity (kV) VLF or ELF fields when given alternatives has been reported (Hilmer & Tembrock, 1970; Schua, 1954).

Few studies have been reported indicating that ELF fields can act as conditioned stimuli. Reille (1968) exposed pigeons for 5 sec. to a 0.15-gauss field that was followed by a 0.5-sec. shock. Increases in heart rate after the presentation of the field but before the onset of shock were noted for static, 0.2-Hz to 0.5-Hz and 300-Hz to 500-Hz fields. The greatest ELF-associated increases occurred with the 0.2-Hz and 0.5-Hz field. The static field had a much weaker effect. Failure to react to static fields or ELF fields greater than 100 Hz at higher than natural intensities has often been reported (Emlen, 1967; Meyer & Lamb, 1966; Orgel & Smith, 1954). Similar frequency dependence on possible learning behavior was reported in an unpublished paper by La Forge.[5] Rats were trained to press a lever for water reinforcement and then exposed 45 min./day for 2 days to either a constant, 0.2-Hz or 2.0-Hz magnetic field of about 800 gauss or control conditions. When tested for number of lever presses 24 hr. later, no significant differences were found between the number of lever presses displayed for control or constant field rats. Rats that had been exposed to either a 0.2-Hz or 2-Hz field showed significantly fewer lever presses, especially those which had been exposed to the 0.2-Hz field. La Forge interpreted this effect as decrements in learning. However considering the reports of Persinger, *et al.* (1972), increased activity in the rats exposed to 0.2-Hz or 2-Hz fields could also explain the decrement in lever presses.

Two areas of research which also include ELF phenomena: magnetophosphenes and electroanesthesia, are not covered here since stimuli for these effects are not often found in nature. Phosphenes and mixtures of wavy luminous effects in the visual field, especially in the temporal regions, occur when ELF fields greater than 100 gauss are applied. The effect is frequency dependent and peaks between 20 Hz and 30 Hz. An extensive discussion and theoretical interpretation of this phenomena has been reported by Valentinuzzi (1961). Anesthetic, cardiovascular, and other autonomic changes can be produced by applying 1-mA to 10-mA, 1-Hz to 10-kHz currents to the nervous system. The anesthesia induced by transtemporal electric currents can be potentiated by 5-Hz pulses (Photiades, Riggs, Ayivorh, & Reynolds, 1970). Similarly, Becker (1969, 1965) notes that EEG changes from electronarcosis are more readily potentiated with .1-Hz pulses than with 10-Hz or 100-Hz pulses and that the effect may be mediated via the transcephalic dc potential system. Shifts in the polarity of these fields are known to be associated with a variety of RT (Friedman & Taub, 1969) and other behaviors (Rowland, 1968) and could be coupled to ELF fields (< 1 Hz). A thorough review of electroanesthesia has been prepared by Herin (1968).

Physiological and Biochemical Changes

Lotmar and Ranscht-Froemsdorff (1968) reported that respiration rates of

[5]H. LaForge, Effet d'un champ magnétique de 800 gauss sur un comportement appris. (In preparation, 1973)

rabbit tissue showed considerable day-to-day variability. Arguing that these variations were associated with 400-mV/m pulses from local sources of tropospheric lability, they correlated these pulses with the measured daily respiration quotients. It was found that labile weather conditions (cyclonic), characterized by 400-mV/m pulses, were significantly correlated with decreased respiration while fair weather conditions (anti-cyclonic) resulted in increased respiration rates. Similar decrements in oxygen uptake have been noticed during low pressure frontal movements in Western Europe or with maxima in 3-kHz to 50-kHz, 0.4-V/m frequencies (Damaschke & Becker, 1964). Increased geomagnetic activity, which can be associated with sub-ELF geomagnetic pulsations (Tepley & Amundsen, 1964) is followed 2 or 3 days later by decrements in oxygen uptake in snails (Barnwell, 1960). Experimental verification of these correlations was later reported by Lotmar, Ranscht-Froemsdorff, and Weise (1969). Exposure of fresh mouse liver tissue to artificial "bad weather impulses" characterized by 30-Hz to 100-Hz pulses with 10-kHz to 100-kHz carriers at greater than 100 mV/m resulted in a 42% decrease in respiration rate. The separate application of only the magnetic component had no effect. "Good weather impulses," 1 Hz to 3 Hz, less than 10 mV/m, and with 10-kHz carriers also showed no effect, although more intense 1.75-Hz fields reduced oxygen uptake (Altmann, 1969).

A few studies indicate the role of the brain-endocrine system with ELF effects. Popa (1969) noted that guinea-pigs exposed to 50-Hz to 100-Hz fields showed an activation of the adrenal cortex. In four experiments, with 8 to 12 rats in each experiment, Persinger, Glavin, and Ossenkopp (1972) measured circulating eosinophil levels, adrenal weights, testicle weights, and thyroid weights of rats exposed to a 0.5-Hz, 0.5- to 30-gauss rotating magnetic field (RMF) or control conditions. No significant differences between RMF-exposed and control groups were noted with the first two measures. Animals exposed to the RMF for 10 days or 26 days showed increased testicle weights, only the latter being statistically different from controls. Relative thyroid weights in the RMF-exposed group were significantly less than controls in the 10-day exposed animals, although in all four experiments the RMF-exposed groups showed greater variance in weight of this tissue. Body-weight gains were noticed in the RMF-exposed groups as well as increased water consumption. The latter changes in RMF-exposed rats had been reported earlier (Persinger, 1967). Persinger and his associates suggested that these results along with increased aggressive behavior, indicated increased thyroid activity, since many of these behaviors have been associated with hyperthyroidism. Interestingly enough, increased I^{131} uptake in rodents, implying increased thyroid activity, has occurred during labile weather conditions (Frey & Goeke, 1969), when high intensity ELF pulses are generated.

Cardiovascular Effects

The ELF-electromagnetic component of weather fronts has been implicated

in human cardiovascular disorders by Brezowsky and Ranscht-Froemsdorff (1966). During periods of the year when .02-V/m ELF pulses showed double peaks during the day, a significant number of myocardial infarcts occurred before the minima and shortly after the maxima. Mortality cases diagnosed as "cardiac infarct" showed a more statistical distribution over the day. These authors point out that the period of curve inflections is also the period of switch-overs in the autonomic nervous system and postulate difficulties in cardiovascular feedback mechanisms. Other studies on myocardial infarction have produced results commensurate with the conclusions of Ranscht-Froemsdorff and Brezowsky. Teng and Howard (1955) noted that the majority of myocardial infarctions occurred when the person awoke and was at rest, during the period of autonomic switch-over from para- to orthosympathetic dominance. These authors emphasize that many attacks occur inside, out of the elements, and when the frontal system is just approaching. Since the lower end of the ELF band (within cardiofrequency) would both precede frontal systems and penetrate buildings, ELF-cardioelectromagnetic interaction might occur.

Ranscht-Froemsdorff (1969) has emphasized frequency specificity in autonomic-ELF effects. Supposedly, the parasympathetic nervous system, which is dominated by the vagus nerve, is sensitive to frequency modulation of ELF waves and pulses, with special sensitivity in the small band (1 Hz to 100 Hz) associated with distant pulses. The orthosympathetic nervous system on the other hand is more affected by changes in amplitude of the pulses and broad-band waves in the kHz range. Ludwig and Mecke (1968) emphasize that, in addition, the stability and dominance of the ortho- or parasympathetic systems are important. According to their scheme, it is the labile vagotonic individual with such symptoms as unstable cardiovascular responses, who is most receptive to ELF influences. Although experimental support of these contentions is required, several studies have shown (e.g., Tromp, 1963, p. 196) that parasympathetic reactions seem to take place 5 to 6 hr. before the passage of frontal systems. During this time distant ELF pulses of lower frequency would exhibit maxima power spectra in the organism's environment. The orthosympathetic system, on the other hand, shows a stronger reaction 3 to 5 hr. after passage of a frontal system. These periods would indeed be characterized by higher frequency wave bands and a larger range of amplitude changes.

Available data indicate two processes by which ELF fields could influence the cardiovascular system: "driving" and "clotting." We have already reported Wever's research with weak 10-Hz electric fields as resynchronizing agents for desynchronized circadian rhythms in human *Ss*. It is also conceivable that under situations of cardiac failure, natural ELF fields might act as Zeitgebers. In this situation, a failing heart system would utilize cardiofrequency signals of distant ELF sources, since ELF sources of closer proximity would be above the presumed effective frequency range. As the ELF source approached or passed tangentially to *S*

and the incident frequency changed, the ELF-driven heart could no longer maintain synchrony with these fields and consequently begin failure sequences. That cardiofrequency electromagnetic fields may act as transient "drivers" of at least rat heart systems has been shown by recent experiments (Persinger, 1973). In these experiments, rats that had been exposed during successive doses of pentobarbital for approximately 4 hr. to a 0.5-Hz rotating magnetic field (1 to 20 gauss) showed contraction rates within the field range significantly longer than either control field or sham-field rats before cessation of QRS (heartbeat). It is important to emphasize that these animals were already in a cardiac failure sequence. Exposure of rats to higher frequency fields approximating normal heart ranges does not seem to be effective.

The second vascular phenomena often associated with ELF waves or ELF wave correlates (e.g., frontal passages) are clotting-related disorders. Halse and Quennet (1948) noted an increased hyperprothrombenemia and thromboembolism with low pressure frontal passages. Indirect involvement of ELF fields upon blood flocculation (Takata, 1951), and (human) blood sedimentation rate (Tromp, 1967) has been suggested. Experimentally, both blood coagulation and the precipitation of colloids in water solution have been shown to be affected by ELF or VLF exposures (Eichmeier & Ruger, 1969; Piccardi & Cini, 1956). Fischer, *et al.* (1968) noted that the mobility of suspended colloid particles was accelerated with 10-kHz fields, especially at intensities approaching natural conditions. Measurements by Boenko and Shakhgel'dyan (1968) of rabbits exposed to a 8-kHz 1500-V/m electromagnetic field for 10 min. showed decreases in coagulation time. They suggest that this audio-frequency electromagnetic field may affect the processes of blood coagulation via the reflexogenic vascular zones. Ranscht-Froemsdorff (1969) reports Kummel's claim that post-operative embolisms can be avoided by placing patients in a thick steel room, a procedure which could eliminate the VLF carriers of ELF pulses. Although these data suggest a direct effect on blood-clotting properties as a possible contributory stimulus to vascular failures, the role of the thyroid-endocrine complex should not be forgotten. Thyroid changes have been reported following long-term ELF exposure in rats (Persinger, Glavin, & Ossenkopp, 1972) but this tissue can also show colloidal changes within 10 min. following an effective stimulus (Shishiba, Solomon, & Beall, 1967). Hyperthyroidism often produces auricular fibrillation and other supraventricular arrhythmias (Papp & Szekeres, 1971). Patients following myocardial infarctions show hypothyroid-like symptoms such as less bound thyroxine (Felt, 1969). The more specific role of thyroid activity and blood clotting has been discussed by Tudhope (1969).

Pre- and Neonatal Exposure Effects in Rats and Ducks

There is no doubt that the developing organism is very susceptible to such environmental factors as ionizing radiation, hormone injections, or nutritional

deficits, which have been demonstrated to have long-lasting effects on biochemistry, cytoarchitecture, physiology, and behavior. In the CNS alone, during the development of the fetus there are many processes which might be influenced by ELF or VLF exposure. Cells migrate from their proliferative matrices, axons grow by processes (which are still unclear) to particular nuclei, and chemical systems later associated with behavior (catecholamines, indols) are synthesized during this period.

Persinger, Ossenkopp, and their associates have demonstrated that prenatal exposure to a 0.5-Hz, 0.5- to 30-gauss (10^{-5}-V/m) rotating magnetic field (RMF) can result in a variety of behavioral and physiological changes. Rats, exposed continuously during prenatal development to this ELF field but removed at birth, displayed less ambulatory behavior but greater defecation in an open-field test when compared with controls at 21 to 25 days of age (Ossenkopp, 1972; Persinger, 1969). Both Persinger (1969) and Ossenkopp (1972) reported greater decrements in ambulation for male rats relative to female rats exposed to the RMFs, although statistical significance was evident only in the former study. When attempts were made to isolate environmental factors responsible for the larger variance of ambulation noted in RMF-exposed litters, a significant correlation of .877 was found between juvenile ambulatory behavior and lunar distance at the time of litter birth (Persinger, 1971b). Lunar distance at birth did not correlate significantly with ambulation in the control litters. The implications of these correlations are still unclear.

In a free-operant avoidance situation, where the animal could postpone an electric shock by pressing a lever, the ELF-RMF-exposed rats showed significantly less bar pressing but received similar number of shocks relative to control animals (Persinger & Foster, 1970). Suggesting these results indicated that the ELF-exposed rats were attenuating their responding or "freezing" in the presence of aversive stimuli, Persinger and Pear (1972) tested ELF-exposed and control rats in a conditioned suppression task—a situation in which any "freezing" of ongoing behavior would be amplified. In three experiments it was found that during the first few pairings of CS with electric shock, the ELF-RMF-exposed rats did show significantly more suppression of response rate during the CS periods. Consequent pairings at the same shock intensity resulted in similar suppression rates in the control groups. Persinger and Pear concluded that the data thus far collected implied an increase in autonomic reactivity to novel or aversive stimuli, including the anticipation of aversive stimuli, by the ELF-RMF-exposed animals.

Since similar behavioral patterns have been shown in rats with hypothyroid-like symptoms (e.g., Feuer & Broadhurst, 1962; Yeakel & Rhoades, 1941), Ossenkopp, Koltek, and Persinger (1972) examined the thyroid tissue of RMF-exposed and control rats. They found a significant increase in relative thyroid weight in the experimental animals, relative to controls. The differences were dependent

upon exposure intensity and duration. Unfortunately no histological examination of the tissue was attempted. In addition, the RMF-exposed rats also showed a significant increase in relative testicle weights. A fourth experiment which compared animals that had been exposed to the RMF apparatus with the magnets removed (sham-field) to animals exposed to usual control conditions resulted in no significant weight differences in these tissues. Differences in circulating blood eosinophil levels and blood sugar between RMF-exposed and control groups were also not significant.

Ossenkopp (1972), suggesting that such changes might be residual effects of an earlier hypothyroid-like state associated with prenatal RMF exposure, recorded eye opening, teeth eruption, and startle reflex development in rat pups from RMF and control litters. He found no consistent differences between groups with respect to the startle reflex development but significant retardation of teeth eruption and eye opening in the RMF-exposed pups. The latter two properties are characteristic of relative hypothyroid animals. If these effects are consistent, then definite changes in the CNS as well as other parts of the body might have occurred also. It has been shown that thyroidectomy at birth results in hypothyroid-induced disruption of granule cell migration and Purkinje cell dendritic arborization in the cerebelli of rats (Hamburgh, 1969), aberrant cytoarchitecture in some cerebral cortical layers, and alterations in cholinesterase (Geel & Timiras, 1967), hexose monophosphate shunt enzymes (Schwark, Singhal, & Ling, 1971; Singhal & Ling, 1969) and other chemicals systems (Hamburgh, 1969; Krawiec, *et al.*, 1969).

It has been reported that the time of pre- or neonatal exposure to *ionizing* radiation results in different CNS and peripheral effects, depending upon the developmental condition of the tissue-chemical systems affected (e.g., Furchtgott, 1963). Similarly, exposure to ELF-RMF conditions on fetal Days 13 to 16 and post-natal Days 1 to 4 resulted in different behaviors. Persinger (1971a) tested these pre- and neonatal ELF-exposed rats and their controls on a delayed conditioned-approach situation (Halasz, 1968), which utilized the step, impulse and ramp signal procedures of schedule change. Applications of such changes to reinforcement delivery are associated with *transient* behaviors which can differentiate populations of animals that are not discriminable by more static schedule procedures (Halasz, Hughs, Humpherys, & Persinger, 1970). Essentially, in the modified DCA paradigm used by Persinger (1971a), rats were trained to press a bar for water reward in the presence of a tone and not to press during its absence. A week later, half way through the session, a 10-sec. delay was instituted in a step-like manner so that water reward was now delayed for 10 sec. after the onset of the tone. The prenatally exposed RMF rats did not differ from their controls with respect to responses emitted during the delay period. However, the rats that had been exposed to the RMF during their first three postnatal days, showed significantly greater response numbers during the delay period than controls or the

prenatal animals. This effect was transient and attenuated on the consequent session. Such behaviors seem to be associated with the cerebellum, certain parts of which (vermis) were maximally developed during neonatal Days 1 to 4. Although significant differences in cell layering or formation were not apparent between neonatally RMF-exposed rats and controls, it is more likely that changes would be in thyroidectomy-affected cell processes such as dendritic arborization or changes in glial cell function and capillarization. These structures are susceptible to environmental modifications. For example, capillarization of rat and other mammal brains can show ± 20% changes in density and length as a function of changes in oxygen supply (Friede, 1966, p. 11). The role of oxygen uptake in ELF processes has already been implicated and will be discussed more fully in the next section.

All prenatal studies with viviparous animals encounter problems of mother-fetus interaction. To obviate such difficulties, a new trend in prenatal ELF research has been initiated by Ossenkopp and Shapiro (1972). They have exposed White Peking duck eggs (during prenatal development) to 0.5-Hz rotating magnetic fields of 2 to 10 gauss or 10 to 30 gauss and control conditions. In order to shield out VLF carriers of ELF pulses, both field and control areas were contained within a radio-shielded room. Open-field tests with the ducklings showed a "dose-dependent" trend for increased ambulation and significantly greater defecation frequencies in the RMF-exposed ducks. The young ducks that had been exposed prenatally to the 2- to 10-gauss fields showed significantly greater hatch weights and increases in foot length over a 7-day period. Comparable increased body weights (relative to higher intensity or control groups) have been noted in rats that had been exposed during prenatal Days 13 to 16 to a 0.5- to 2-gauss, 0.5-Hz field, but not in groups exposed to these intensities during prenatal Days 1 to 21 or neonatal Days 1 to 4. Both rat and duck studies strongly indicate reliable changes in emotional behavior and other endocrine-mediated behaviors following prenatal exposure to 0.5-Hz rotating magnetic fields.

Possible Mechanisms

There are several mechanisms by which ELF electromagnetic fields might affect living tissue and animal behavior. For our purposes, these approaches can be designated according to level of discourse: atomic-paramagnetic effects, molecular-structural effects, resonance effects of cell-organ electrical and mechanical systems, and neurovascular-behavioral effects.

Since ELF electromagnetic fields have magnetic components that often approach d.c. or near static field conditions, the role of two paramagnetic substances should be considered: iron and oxygen. The energy from the magnetic component of ELF fields available to the ferric ion would be negligible compared to that from thermal agitation. In fact, according to elementary equations, most high intensity static magnetic fields used in laboratory research do not approach the

required values to correct for thermal agitation at life-temperatures. The oxygen molecule, on the other hand, might be affected by influencing its *rate* of chemical reaction. Valentinuzzi (1961) has remarked that the effect of a static magnetic field will be to maintain the strongest paramagnetism of the substance in question. If these assumptions are correct when low-enegry ELF fields are involved, then molecular oxygen, which is paramagnetic, would be prevented from going into a reaction which would transform it into a diamagnetic state, such as oxyhemoglobin. Changes in oxygen uptake have been noted following ELF exposures, but seem to be dependent upon the field frequency within a very narrow band, and suggest involvement of some other process.

ELF-field effects could be mediated at a more complex molecular level by interactions with specific structures. The frequently reported changes in oxygen uptake in tissue, blood clotting, flocculation and sedimentation rates of erythrocytes during ELF-field exposure strongly suggest the role of one important structure: hemoglobin. Hemoglobin contains a haem (iron) component and during various stages changes from oxyhemoglobin to deoxyhemoglobin, a process involving oxygen transfer. It is known that the hemoglobin molecule is extremely sensitive to small alterations of internal non-polar contacts near the haems and at contacts between α and β subunits (Morimoto, Lehman, & Perutz, 1971). The latter displacements affect respiration, an apparent fundamental factor involved with ELF effects. Decrements in both hemoglobin and respiration have been shown in young pubescent mice housed in Faraday cages, a procedure which would presumably attenuate the VLF carriers of ELF pulses (Lang, 1972).

ELF fields may not act specifically only upon hemoglobin, but, for some unclear reason, influence a certain family of molecular structures which include hemoglobin. For example, the orientation of the benzimidazole ring in the Vitamin B_{12} molecule is strikingly similar to the orientation of the pyridine ring in the hemoglobin molecule (Rodley & Robinson, 1972). Insufficient amounts of this vitamin result in pernicious anemia, a condition which is characterized by fragile membranes in erythrocytes. Such changes in membrane configuration would have cascading consequences and produce changes in oxygen-membrane transport, erythrocytic oxidative enzyme activity or even sedimentation rates. Because of the low energy density, ELF effects would involve susceptible structural interactions rather than gross chemical reactions.

Several theoretical papers by Ludwig (1972, 1971, 1968) have shown that ELF electromagnetic fields may act upon living organisms though the mesophasic structures of the body known as liquid crystals. Liquid crystalline or paracrystalline states occur when certain macro-molecules in a liquified condition take on an ordered or crystal-like structure. It is well recognized that phospholipids, one of the basic constituents of the axon and essential for the resting and action potentials, undergo a phase transition to a liquid crystalline state when the tempera-

ture, pH, and water concentration of the system are optimal. In vitro experiments indicate that various phospholipids (e.g., phosphatidylcholine) can display pH and divalent cation-dependent properties characteristic of nerve membranes. That such states exist in living organisms has been discussed extensively by Stewart (1969, 1961, 1959).

Of the three phases of liquid crystals (nematic, smectic and cholesteric), the nematic and smectic structures are found in cell membranes and tissue. In these two phases, in contrast to normal fluids (without order), there are *two* dielectric constants, depending upon the orientation of the externally applied field with respect to the molecular axis. If the field is applied vertically to the molecular axis, the normal Debye-dispersion is in the microwave region; if the field is parallel to the molecular axis another factor involving the high intermolecular forces of the molecules occurs and shifts the dispersion frequency into the LF and VLF region. In general, a cell membrane has four molecular layers. Apparently inside of the membrane lie two protein layers which are each covered with a lipoid layer, the aliphatic chains of which face outward. Of these membranes two are very close together as a consequence of electrostatic forces. Through electrostatically controlled elastic tensions, retrograding forces appear in the above cases where molecules vibrate in the rhythm of the external alternating field. During resonance absorption involving the synchronous vibration of the molecules with external field, energy can be derived from the field. In addition to these inner elastic torsion vibrations, there is also a transverse natural resonance which lies in the kHz region. According to Ludwig's equations a swinging motion in the membrane with the applied ELF-field frequency would result in a change in the size of the membrane pores during which time changes in the ionic milieu about the synapse could occur, thus changing the resting potential of the membrane. Calcium ions theoretically would be most affected. Once depolarization of the membrane has occurred both the membrane tension and resonance frequency would be lowered. Such perturbations would be especially prominent in long myelinated axons with cable properties. These effects would occur with a band of VLF frequencies because of the varying pre-stimulation values of individual membranes. How the ELF wave would interact with molecular structure or weak transmolecular electric fields has not been described.

Liquid crystals will also display different physical reactions to different ELF-VLF frequencies. Such experimental evidence is important in the light of often reported frequency dependence of ELF-VLF effects. Parker and Carr (1971) showed that a nematic crystal with a negative low-frequency dielectric anistropy may be observed to align with the long molecular axis preferring an orientation parallel to a high-intensity ELF field but perpendicular to a VLF field (Parker & Carr, 1971). Carr (1970) hypothesized that this is due to field-induced space charges along boundaries of misaligned regions being unable to perturbate above a certain cut-off frequency with the field.

It is not surprising that water, the major component of living fluid systems, has also been theorized to show structural changes to low-energy ELF and VLF sources. Piccardi (1962) has speculated that at certain temperatures, water can be viewed as a liquid crystal containing bonds which permeate the entire liquid, thus allowing summated effects from small energy sources. However, examination of research in physical chemistry concerning the structure of water shows a controversial history which has been discussed elsewhere (Eisenberg & Kauzmann, 1969).

The problem of how ELF effects are mediated to tissue systems must involve the biochemical substrates discussed, some unique configuration of the cell-organ complex, or an interaction of the above. Ludwig (1972) has suggested that the altered sequences of conductive and relatively nonconductive layers in axons or fiber tracts might act as an antenna and amplify weak signals. The frequency specificity is implicit in his equations since solutions indicate a maximum ELF effect in areas (CNS) of greatest synaptic densities (Ludwig, 1971). The opposite would hold for the VLF band, where maximum effects would occur in the less synaptically dense peripheral nervous system (Ludwig, 1968).

A model similar to that of Ludwig's has been employed by Russo and Caldwell (1971) and suggests another means by which the amplification of weak ELF signals might be achieved. They suggest that the neuroglial complex can behave like a P-N semiconductor. A semiconductor is composed of two crystals of the same substance but with different electrical properties due to impurities introduced into it (e.g., the introduction of indium or arsenic into a germanium crystal). Glial and neuronal membranes do show an ordered structure (liquid crystal) but differ in electrical properties, the action potential of the glial component being about a 1000 times longer than the neural component (Tasaki & Chang, 1958). If the neuroglial complex did act as a semiconductor with P-N junctions, it would have properties of ionic barriers, directional control of current, susceptibility to electromagnetic fields, and power amplification. Transistors, for example, can amplify microwatt signals into signals in the order of milliwatts. The glia cell, an integral part of the Russo-Caldwell model, would be also most susceptible to the types of processes involved in ELF effects. Astroglia are important for oxygen transport to the neuron as well as other interactions with the vascular systems. The oliogdendroglia, on the other hand, with their high concentration of pentose shunt enzymes, are important for the production of the paracrystalline myelin structures.

On a higher organizational level ELF effects may exert their influence through a type of resonance interaction with various systems of the living organism. Most physical structures have "natural frequencies." Such structures, when subjected to continued application of "natural frequencies" at low energies, show marked perturbations. An example is a suspension bridge which can be destroyed with the appropriate low frequency vibration. The skeletal musculature has a

natural resonance between 4 Hz to 12 Hz while the visceral muscles show resonances at lower frequencies (< 1 Hz). One characteristic of autonomic neurons is to maintain electrical activity with stimulation of less than 1 Hz. Heart muscle stands as an interesting intermediate between smooth and skeletal muscle both in construction and resonance frequencies. Amplification of the vibration frequencies of skeletal muscles can take place with relatively negligible amounts of internal energy, as is presumably the case in shivering. At such low energy levels, interaction between applied ELF fields and skeletal-visceral muscles must occur within very narrow frequency bands approximating that of the resonance frequency of muscle. Fish have been shown to be responsive to magnetic field frequencies approximating their own electrical systems and harmonics of these frequencies, although other bands can also be effective (Werber, Sparks, & Goetz, 1972).

If effective low-energy ELF fields are summated over a macroresonating system of the body, dissipation of the energy must take place or the system could begin a positive feedback oscillation resulting in marked disarrangement of vital structures. In the nervous system some energy could be dissipated simply through the elastic reactions of the liquid crystalline structures. A second means could be through the electrical systems which have frequencies similar to that of the applied field and whose function is to *modulate* changes in the neuronal electrical activity. Glial cells would fit these prerequisites. They have been shown to demonstrate pulsatile behavior in the ELF range for gross cytoplasmic contraction and electrical activity. Glial cells would also be most susceptible to any perturbations in the liquid crystalline myelin structures, where differences in feedback could change fatty acid sequences. Such stimulation of glial components would again interfere with neuronal respiration as well as interactions with the vascular system. Basic neuronal-humoral respiration reactions would require glial cells since they contain a much greater concentration of carbonic anhydrase than do neurons. Carbonic anhydrase, a zinc-containing metalloenzyme, is also highly active in red blood cells of homothermic animals and catalyzes the rapid excretion of carbon dioxide from the blood. That glial cells are often the first cytological structures to show pathology to low levels of many types of ionizing radiation is known. Glial reaction to static magnetic fields has been reported by Kholodov (1964), but recent experiments by Friedman and Carey (1972) have failed to replicate this observation. An earlier publication by Friedman and Carey (1969) reported small amounts of glial histopathology in the brains of monkeys that had been exposed to 0.1-Hz or 0.2-Hz magnetic fields for 60 hr.

On the physiological-behavioral level, mathematical calculations and empirical observations indicate that the ELF effect should be mediated through the high membrane density areas, especially the neuro-vascular interfaces. Included in these interfaces would be the hypophyseal structures and paraventricular and supraoptic nuclei of the hypothalamus, all of which are among the most highly

vascularized areas of the mammal brain. ELF electromagnetic effects could be mediated directly through small energy summations in these high membrane concentration areas or indirectly through exposure of these areas to blood chemistry changes from direct endocrine-chemical disturbances. A third alternative is that ELF-induced direct changes in the chemical composition of the blood (or water) would have indirect effects by interacting with the highly vascularized brain-endocrine tissue. Many of the observed ELF-associated behaviors including RT differences in primates, subjective complaints by human *S*s, ambulatory changes in rodents, cardiovascular difficulties in mammals and respiration-biochemical differences in tissue and blood, are of the small magnitudes typical of those produced by other manipulations of hormonal levels.

Persinger, Glavin, and Ossenkopp (1972), in an attempt to explain the apparent contradiction between prenatal and adult exposure behavioral and physiological effects in rats, suggested that the thyroid chemicals were involved, especially because of this tissue's concentration of colloidal structures. During ELF exposure both the mother and fetus would be exposed to a relative hyperthyroid environment. Once the neonate was born and removed from the fetal environment, a relative hypothyroid condition, compared to controls, might develop. These *E*s did not present data to support this contention and it is just as probable, as suggested by Ludwig (1971) that the hypothalamic-median eminence-hypophyseal system could be primarily responsible and that the thyroidal consequences are purely secondary. Recent experimental work by Halmy, Nyakas, and Endroczi (1971) indicate this possibility. The thyroid hormones are important for oxidative processes and are involved with enzyme systems(hexose monophosphate shunt) and cell structures (glial mitochondria) which are involved with myelinization and electrical changes in the CNS. As mentioned the pentose shunt enzymes are especially influenced in rats by thyroidectomy and consequent hypothyroidism. The similarities between hypothyroid-like rats following selective breeding (Maudsley Reactive Strain) or neonatal thyroidectomy (Eayrs, 1968) with prenatal-neonatal ELF-exposed rats has been mentioned. Hypothyroid and erythrocytic-pentose shunt reactions can also affect the important vitamin B complexes. Deficiencies in the vitamin B complexes produce many of the symptoms noted in correlational and experimental ELF studies. From the above data, one might predict that in terms of structural changes in the brain, little modifications should be seen in neuronal patterning in the brain of rats exposed pre- or neonatally to the ELF fields approximating natural intensities. The maximum effects should occur in the more environmentally responsive capillary densities, glial cell concentrations and dendritic processes.

Conclusions and Suggestions

Although no clear, consistent relationship has been shown between ELF-bio-behavioral effects and the physico-chemical substrates, the following conclusions can be made from the available data concerning ELF electromagnetic fields.

1. *ELF-occurrence.*—ELF electromagnetic waves and ELF pulses on VLF carriers (10 kHz to 100 kHz) occur in nature and are associated with weather conditions, geomagnetic fluctuations, solar eruptions, and household electrical apparatus. Because of their low frequency they can penetrate buildings and are potential biological stimuli. They occur within the frequency range of bio-electrical phenomena.

2. *ELF physical properties.*—Although natural ELF fields have low intensities in electrical ($<$ 1 mV/m to 1000 mV/m), magnetic (10^{-8} gauss, 10^{-5} A/m), and power (10^{-8} watts/m^2) components, they could interact with electrical processes in living tissue. The energy available from these fields is well within the magnitude to trigger receptors and influence miniature EPSPs. Amplification of natural signals is possible since tissue, especially CNS tissue, displays liquid crystalline and semiconductor properties.

3. *Main effects.*—The ELF-effect seems to involve timing behavior in mammals. Consequently, disturbances in reaction time in primates, ambulatory behavior in rats, circadian variations and time perception of human beings, along with electrical changes in the parts of the brain involved with these changes have been observed. On the physiological level, oxygen uptake in tissue and respiration rates in rodents is affected, a change that may account for the suggested thyroid-hormonal related modifications in cardiovascular and behavioral systems. Chemically, differences in some properties of colloids in water solution and liquid crystals occur which affect sedimentation rates and clotting times.

4. *Frequency dependence.*—The measured changes in RT, ambulation, colloidal suspension rates and brain electrical changes show selected susceptibility to different field frequencies.

5. *Intensity dependence.*—ELF-induced changes exhibit an intensity relationship, static or high intensity fields usually producing different or opposite effects relative to intensities in the natural range.

Several suggestions may be made for future research in this area.

1. *$\overline{E}$ and $\overline{H}$ components.*—The possible differential effects of ELF fields with different electrical ($\overline{E}$) and magnetic ($\overline{H}$) component distribution should be investigated. This may be important since at frequencies below 20 Hz, which include the majority of important bioelectrical-behavioral correlates, there is probably a change-over in nature from dominance of the electromagnetic to the magnetic component (Pierce, 1960; Aarons, 1956). One set of equations indicates that the magnetic component of atmospherics may only induce currents in coil-like elements such as in the reticular formation.

2. *Signal shapes.*—Impulse-shaped ELF fields seem to produce greater behavioral and respiration effects than sinusoidal fields. The relative efficacy of signal shapes should be determined by direct comparison.

3. *Impulse duration.*—In nature, ELF pulses last in the order of 10^{-4} to 10^{-3} sec. (Al'pert & Fligel, 1970; Ranscht-Froemsdorff, 1968). These should be

simulated in the laboratory since some biogenic proteins such as hemoglobin have relaxation times in this range. Attention should also be directed toward pulse shapes propagated by the spherical waveguide (Al'pert & Fligel, 1970) since such signals from long distances might initiate sustained perturbations in molecular-electrical structure.

4. *Directional components.*—Theoretically, in liquid crystals the optimum dispersion frequency will differ depending upon the angle of the field application. In addition, the orientation of the applied field with respect to the geomagnetic field should be stated since natural ELF phenomena could interact.

5. *Adequate shielding.*—More effective shielding should be used. VLF carriers of ELF pulses can be shielded with special Faraday cages. However, lower frequencies, which may interact with experimental fields, should also be controlled if possible. This was not done in many studies (cf. Persinger, 1969; Persinger, Glavin, & Ossenkopp, 1972).

6. *D.C. potential involvement.*—Becker (1969) has reviewed the influence of ELF currents *directly* applied to tissue resulting in modification of EEG-consciousness correlates. He and his co-workers have reported the presence of at least an electrostatic field around organisms. Since d.c. or slow potentials in the brain are associated with learning and memory (DeMott, 1970; Rowland, 1968), possible ELF interactions with these transcortical and transorganismic fields should be considered. It is known, for example, that ambient ELF-EM fields can influence infra-red radiation from the human body (Hartmann, 1967).

7. *Natural intensities.*—Greater use of natural intensities should be made if generalization of results to natural occurrences is to be possible. The assumption that greater than natural intensities will enhance the effect, as in ionizing radiation research, may not be valid. Organisms may show increased sensitivity to a narrow band of natural intensities.

8. *Measurement of natural ELF.*—Correlational studies between ELF phenomena and life processes could be helpful as sources of stimulation for experimental design. This can be accomplished by increasing the number of stations measuring ELF waves and VLF carriers on a national and preferably international scale.

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